GAS SEPARAIION TECHNOLOGY: STATE OF THE ART*

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PURPOSE

The Bocing/NASA-Glenn RC Task Order Contract is a NASA Aviation Safety Program funded research study to perform an assessment of advanced gas separation technologies that have potential to enhance aviation safety. The contract study investigates technologies that address On Board Inert Gas Generation Systems (OBIGGS) for fuel tank inerting and lire protection, and On Hoard Oxygen Gas Generation Systems (OBOGS) for passengers and crew use. To facilitate the assessment, three sequential tasks were identified: Task 1 - the identification of new and existing airplane system requirements; Task 2 - an investigation of the State of the Art of gas separation technologies; and Task 3 - the development of a prototype specification for an OBIGGS/OBOGS gas separation system. NASA is planning to issue an NASA Research Announcement (NRA) for the development of prototype system hardware for laboratory testing. The objective of these designs is to develop systems capable of operating on-board an aircraft to provide inert nitrogen gas for fuel tank inerting and improved cargo compartment fire suppression, and emergency oxygen for crew and passenger use.

RACKGKOUND

Oxygen systems, as currently designed for use on commercial transport aircraft, include both passenger and crew oxygen systems for use in an emergency in the event of a sudden loss of cabin pressure. Passenger oxygen is provided from either compressed oxygen gas cylinders or from solid chemical oxygen generators. The flight deck crew oxygen systems are exclusively stored gaseous oxygen. Additionally, there are on-board portable gaseous oxygen bottles in the passenger cabin available for medical use and for protective breathing equipment. Chemical oxygen generators for passengers in some aircraft models are located in the overhead compartments above the passengers. These generators produce oxygen by chemical/thermal reaction for periods up to 22 minutes. A detailed description of commercial aircraft oxygen systems is contained in the Task I contract study [1].

The carriage and use of oxygen on commercial transport aircraft is required by FAA regulations. However, oxygen in any fonn does pose a potential fire safety hazard because of the extremely high gas combustion temperatures that can be produced by coinbustible materials burning in pure oxygen or oxygen enriched atmospheres. Strict maintenance and handling procedures are required to ensure that stored oxygen does not contact combustible materials.

One part of this report will address new technologies being developed that are capable of producing oxygen gas on board an aircraft that could be used by a large number of passengers and crew during emergency descents. The technologies in this report that can produce oxygen are ceramic membranes, gas liquefaction, and hollow fiber membrane. A fourth mature technology, Pressure Swing Adsorption (PSA) has been addressed and included for baseline performance comparisons with the newer gas separation technologies.

To protect commercial passenger transport from the potential danger of on board fires, especially those that can ignite in inaccessible areas during flight, such as cargo compartments, fire protection systems

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and design techniques have been developed to provide enhanced protection while the aircraft is in flight. Present day cargo compartment suppression systems rely on sealed compartments and use of a unique fire extinguishant, Halon 1301, to control fires. However, the continued use of halon has been banned by the Montreal Protocol because of its adverse effects on the stratospheric ozone layer. Approximately 10 years of research have not resulted in a replacement agent for Halon 1301. All alternative agents have their drawbacks: toxicity, weight, and volume required for performance equivalence to Halon 1301. The University of New Mexico Center for Global Environmental Technologies has been in the forefront of promoting development of alternate agents, and providing the forum for exchange of information and discussion of ideas through their Halon Options Technical Working Conference (HOTWC) held annually in Albuquerque, NM.

There are two principal approaches to fire suppression: decreasing the oxygen concentration or inerting the combustible environment. Either of these methods can be effectively employed for fire containment or prevention. In current commercial airplanes, the fire protection systems discharge halon gas into a sealed cargo compartment to inhibit the combustion process. After an initial "knockdown" application of a Halon 1301 fire extinguishant, additional halon is metered into the compartment to maintain the concentration necessary to suppress /extinguish fires by chemical reactions in the fire zone for longer duration protection. This technique has proven to be highly effective against both open flame and deep-seated fires for lengthy periods and has successfully met FAA regulations for fire suppression. Any replacement agents under consideration will have standards and requirements of performance equivalent to halon as a minimum baseline.

Decreasing the oxygen concentration in air is a method used by which the oxygen level for a fire already in the process of combustion is reduced to a level where combustion can no longer be supported (suppression after combustion starts). Depending on the ignition source, this level is approximately 10-12% oxygen. Oxygen concentrations are kept at 9% or less to prevent ignition.

Inerting an air volume to inhibit combustion can be accomplished by injecting an inert gas such as nitrogen or argon, (gases that neither support nor sustain combustion) to the point whereby combustion cannot he initiated (prevention prior to combustion). Care must be used with a gas such as helium for testing has shown that helium, though inert, can accelerate flame spread in helium/oxygen environments.

This technical feasibility study investigated two principal applications of inerting technology for commercial transport aircraft fuel tanks and cargo compartments. Current applications of fuel tank inerting in use in some military aircraft have demonstrated the potential to reduce greatly the likelihood of fuel tank explosions in combat environments.

Technologies in place or being developed for separating oxygen and nitrogen gases from air are permeable membranes (ceramic and polymer fibers), pressure swing adsorption and air distillation columns and are the subjects of this report. Gas separation devices can separate an incoming stream of air into two exit streams with the composition of one being nitrogen enriched air (approximately ***95%*** nitrogen and *5%* oxygen) and the other being oxygen-enriched air. These types of devices are currently in use in commercial trucks and ships to blanket fresh fruit and vegetables with nitrogen gas for longer storage life.

Many military aircraft in service employ similar gas separation technologies for the generation of nitrogen gas for fuel tank inerting and oxygen for crew breathing, although some older aircraft require use of stored liquid oxygen (LOX) for crew use. The aircraft nomenclature refers to these systems as On-Board Inert Gas Generating System (OBIGGS) and On-Board Oxygen Generating System (OBOGS).

Another quite common technology application for chemically generated inert gas is seen in rapidly inflating automotive airbags and nitrogen gas generators. These pyrotechnic devices are squib activated to produce chemical reactions that rapidly generate the desired gases. Systems of this type can he designed to produce large amounts of gas in a very short time and can be activated or deployed virtually instantaneously. While not discussed in this report, these systems are finding design application for rapid flooding of a contained area with N_2 as the propellant in water mist fire protection devices, as well as for the primary gas ejectors for inflation.

TECHNICAL APPROACH

The technical approach to performing this study was to identify various companies engaged in advanced gas separation technologies that were specified in the contract. On-site visits and in-depth discussions were arranged with each company engaged in the various gas separation technologies. This provided the opportunity to obtain first-hand knowledge of the technology under development and to assess their respective manufacturing and laboratory facilities, all of which were impressive. **All** of the companies visited provided valuable insight into their respective research and development projects, most of which are proprietary or patent covered. Technical data and figures where applicable have been included when they did not divulge protected information.

GAS SEPARATION TECHNOLOGY

Air separation technology encompasses a broad range of methods, sciences, and applications, many of which are well established and have been in use for many decades. Cryogenic separation or air distillation has long been the primary method of providing nitrogen as a commodity gas to the chemical industry. For decades carrier-based Navy aircraft have been supplied with liquid oxygen (LOX) generated by shipboard cryogenic air separation plants employing specialized distillation columns designed for shipboard size constraints and as well as normal ship pitching and rolling excursions. Pressure swing adsorption **(PSA)** has been used for generations to remove gaseous contaminants as well as provide gas streams enriched with either oxygen or nitrogen. Over the past decade, hollow fiber membrane (HFM) technology has undergone a dramatic growth in use as an on-site source for nitrogen enriched air **(NEA)** for chemical, petrochemical, and food processing and transportation applications. There are many vendors and specialists with both general and specialized technical capabilities to design and fabricate air separation systems that can meet the most varied and unusual customer requirements. Even in the aerospace business, **PSA** units to provide oxygen to fighter crews have become an integral part of an aircraft model's production specification.

Besides commercial off the shelf air separation technologies in current use, a number of newer or evolving air separation technologies appear to hold promise for aerospace applications. Three technologies have been identified by **NASA** for technical assessment as to suitability for use in future commercial aircraft **[2]** and are the subject of this paper. They are cryogenic separation of air into oxygen and nitrogen, hollow fiber membrane gas separation, and ceramic membranes for catalytic separation of oxygen from air. Each technology has its unique areas of strength and **PSA** technology can be used as a baseline technology for comparative purposes.

The subject separation approaches differ from one another in the physical and chemical processes that are dominant in each. In PSA the adsorptive characteristics of particular gas species on particular solid surfaces are exploited in the separation. Ceramic membranes use high temperature surface catalytic behavior to selectively collect the oxygen constituent of air. HFM technology relies on differences in Ostwald solubility coefficients of air components to selectively remove gas species from a gas stream. Cryogenic separation relies on classical thermodynamic processes for liquefaction and distillation.

PRESSURE SWING ADSORPTION

In air separation using pressure swing adsorption, air is passed through a column packed with a bed of pellets or powder characterized by high surface are per unit weight of bed material. If this bed material is some form of zeolite, a Na/Ca alumino-silicate, then nitrogen from the inlet air stream will adsorb onto the zeolite surface and the output gas will remain nearly free of nitrogen until all the available collection sites on the zeolite surfaces are occupied by nitrogen molecules (Figure 1) [3].

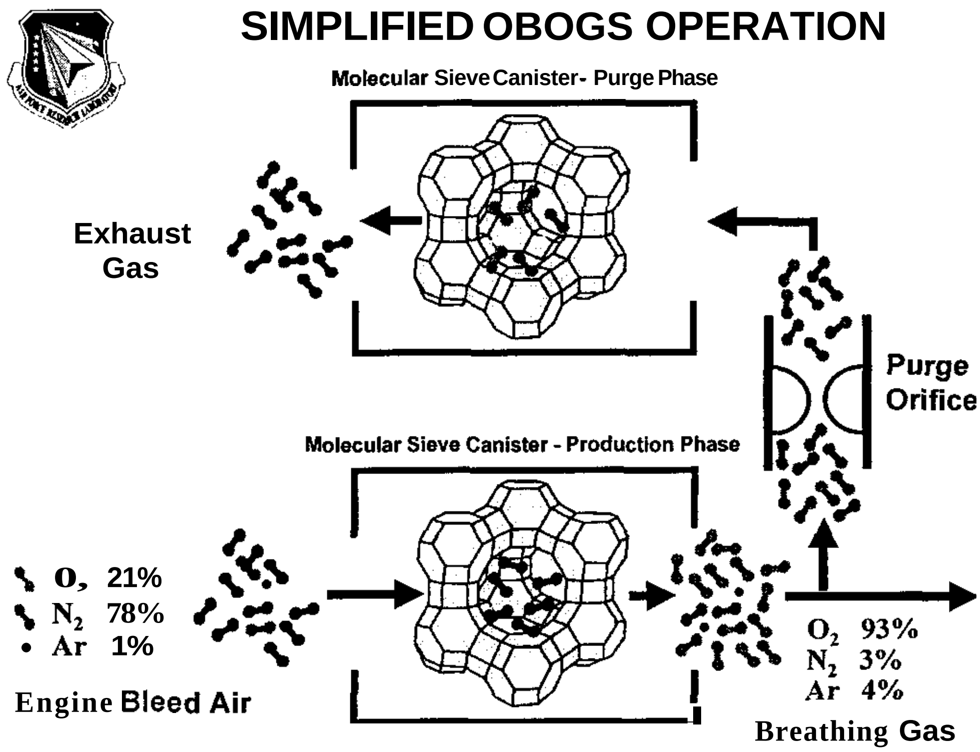


Figure 1. Molecular sieve.

The output gas up to that point will typically be 93% pure oxygen, but will revert to 21% oxygen outflow when the zeolite is saturated with nitrogen. In practice, the inlet flow will be switched to an identical but separate zeolite bed before this saturation occurs. The second bed will then provide the oxygen-enriched outflow until the first bed can be reverse-flow purged of nitrogen and reused in the air separation process. Thus, the air separation process “swings” back and forth between the two beds (Figure 2). In the V-22, both nitrogen and oxygen are produced, one (nitrogen) for fuel tank inerting, and the other (enriched oxygen) for flight crew use.

Producing high purity oxygen by means of a PSA process generally involves use of a second bed with carbon as the bed material because many carbon surfaces will preferentially adsorb argon from an oxygen-argon stream. As with zeolite beds for nitrogen collection, argon will saturate the carbon bed, and the operation will have to be switched to a second bed while the first bed is purged of argon so that it can be ready for use when the second carbon bed gets saturated. The beds for the PSA systems are typically referred to molecular sieves by analogy to screen sieves that separate and collect particles by size.

The PSA units can be used in cycles where the adsorbed gas is the desired product. In the example above, nitrogen would be absorbed when air was passed through the zeolyte at high pressure. However, when the pressure was reduced during the purge part of the cycle, the desorbed nitrogen could be collected and used for an intended application such as fuel tank inerting. In this example, the oxygen-argon outlet stream would be the waste gas. In some applications the gas outputs produced from both the loading and purge cycles could be used for separate intended functions, e.g., NEA for fuel tank inerting and oxygen for crew use.

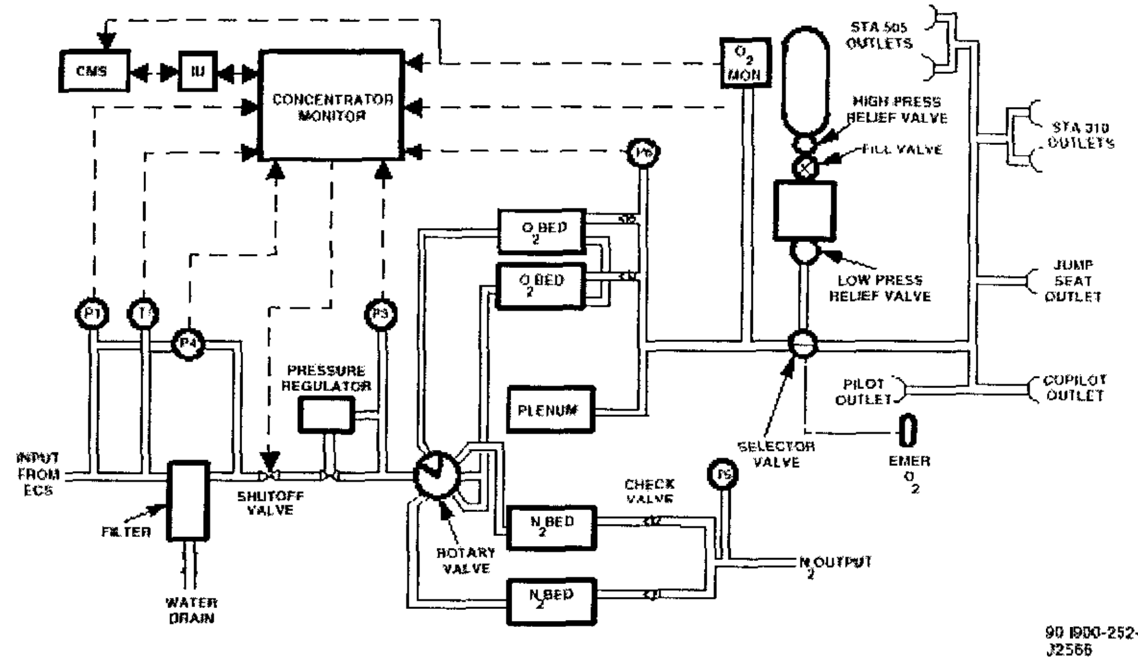


Figure 2. V-22 OBIGGS/OBOGS system

Beyond traditional airplane oxygen supply vehicles (stored high pressure gas bottles, LOX dewars, and solid oxygen generators), PSA is the only technology to have achieved wide-spread application for providing oxygen to airplane crewmembers to date, and it is the only in-use oxygen supply that employs on-site air separation. Litton Life Support is presently the dominant supplier of such PSA systems for producing both nitrogen and oxygen for military aircraft.

In past IR&D projects, Boeing has studied the use of small PSA devices to maintain required **O,** pressures in storage tanks in commercial aircraft service [4]. PSA technology can also be used to provide NEA for inerting of fuel tanks. The military C-5 aircraft set a precedent in fuel tank inerting with their large stored liquid nitrogen systems. The first generation onboard inert gas generating systems (OBIGGS) employing PSA systems have been deployed in the AH-64, V-22 (Osprey), and C-17; however, significant operations and maintenance problems remain of concern.

HOLLOW FIBER MEMBRANES

Hollow fibers are manufactured by asymmetric solution spinning, which is a co-extrusion-like process that allows "composite-like" fibers to be formed in a continuous process. Permeance of gases across a polymeric membrane is based on the solubility of the gas in the polymer as well as the rate of gas diffusion across the membrane. Polymers conducive for high permeance efficiency, lightweight, and reliability are selected for the membranes. A typical fiber is shown in magnified cross section (Figure **3)** where the outside diameter of the fiber is 160-180 microns and the inside diameter is 100-120 microns.

The majority of the fiber wall thickness is a porous sponge-like material that makes up the fiber core. The function of the core is merely to support the outer layer of the fiber that is called the sheath, the boundary layer where gas separation occurs. The sheath thickness is approximately 2-4 microns; it is the outer skin of this layer, measured in Angstroms, that determines the performance of the membrane.

Hollow fiber membranes (HFM) are bundled together by the tens of thousands to form the bundles that make up air separation modules **(ASM)** (Figure 4). On a single fiber basis, air is supplied at one end of

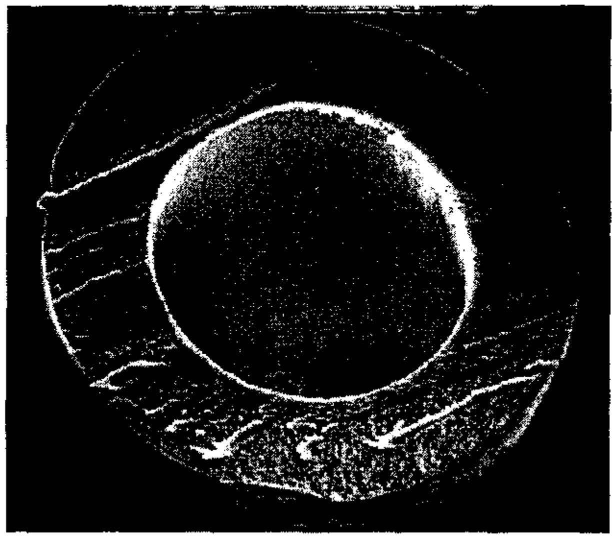


Figure 3. Hollow fiber magnified 1500X.

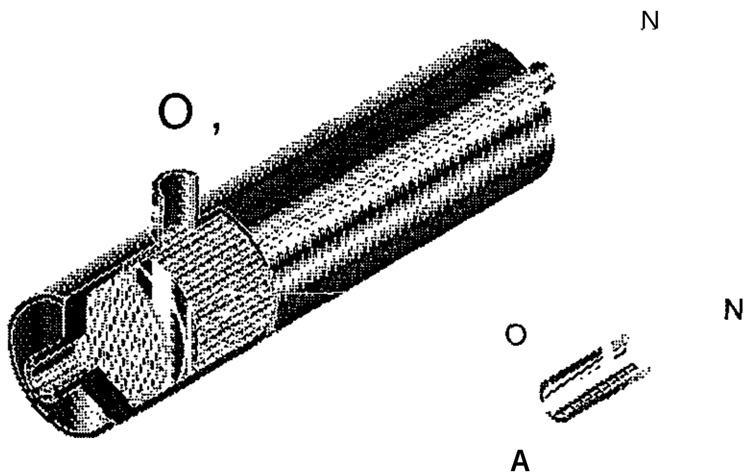


Figure **4.** Typical air separation module construction.

the fiber. As the air moves longitudinally down the fiber, oxygen is preferentially absorbed by the polymer walls of the fiber. Due to the atmospheric pressure difference across the fiber wall, the oxygen that is absorbed by the fiber walls will tend to be desorbed when it gets to the lower pressure. The gas that exits the downstream end of the hollow fiber will have suffered a substantial decrease in oxygen concentration. When tens of thousands of the fibers are bundled together, each works individually as described above, and significant production rates of NEA can be had in the aggregate. **A** schematic of such an assembled bundle is shown in Figure **4.**

Advantages of HFM technology include the lack of moving parts, the low weight and inexpensive nature of the materials of construction, and the lack of any substantial time lag in system start-up. In aerospace applications, the currently involved fiber manufacturers are Permea, Praxair, and Air Liquide with system assembly being performed by either the fiber producer or other aerospace equipment maker, e.g., Valcor or Litton Life Support. In contrast to PSA, the HFM technology is suitable exclusively for NEA production from air. The ASM devices are easily able to generate NEA with nitrogen contents in the low to high 90%. The waste gas oxygen concentration is generally in the neighborhood of 25 to 35%. While oxygen concentrations of up to 95% can be achieved through multi-staging and re-circulation with HFM devices, this has not proven to be a practical approach due to the cumbersome nature of the resulting assemblies. Even for industrial ground installations, PSA represents a comparatively much more effective and less costly approach to separating oxygen from air. An additional problem in attempting to use the HFM waste gas stream is the adverse effect on NEA production efficiency caused by raising the back pressure on the exterior sides of the hollow fibers.

CERAMIC MEMBRANES

Ceramic membranes for separating oxygen from air represent a rapidly developing technology with keen competition among rival manufacturers. This technology uses the catalytic properties of the interior surface of specialized ceramic material to ionize and then separate the oxygen component from the air. In part because of the oxygen ionization process at high surface temperatures, the product gas from the ceramic membrane systems is virtually 100% pure oxygen with no possibility **for** the presence of biological or toxic chemical components. Figure 5 shows a simplified schematic of the manner in which these membranes operate. The ceramic operating temperatures are in the neighborhood of 700 °C and the electrical potential difference across the membrane is on the order of a volt. Presently, this technology goes by a variety of names, some of which are registered trademarks. Air Products and Chemicals, Inc., uses the terminology Solid Electrolyte Oxygen Separation (SEOS) and considers this technique as one subset of a number of Ion Transport Membrane (ITM) technologies. Air Liquide also uses the SEOS terminology. Litton Life Support calls its technology the Ceramic Oxygen Generating System (COGS).

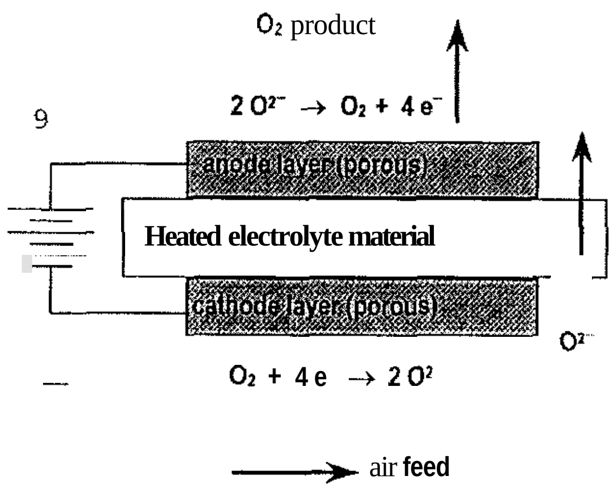


Figure 5. Ion transport membrane.

When ceramic membrane devices are built in practice, they have three valuable characteristics — the first two of which are unique among air separation technologies. First, the ceramic membranes require no moving parts, and this feature has obvious reliability advantages — particularly attractive in aerospace applications. Second, the ceramic membranes are insensitive to supply air contaminants. All the other air separation technologies suffer sensitivity to one form or another of supply air contamination or moisture or the minor constituents of air. Third, the deterioration and failure of a ceramic membrane can be readily detected due to a fall-off in the pressure of the output oxygen pressure. **In** the typical devices built so far, these oxygen output pressures are in the neighborhood of 2000 psia.

The efficiency of ceramic membrane devices is affected by the geometry of the membranes, the solid electrolyte material constituents, the operating conditions, and the design features for the supply air flow and heat transfer. Presently, the devices are heated by electrical resistance devices, which causes a time lag before a unit can be brought up to full oxygen production rates. However, future devices might use more controllable heating techniques, e.g., focused microwaves, lasers, or acoustics. Expelling the waste heat is a design consideration that must be taken into account as well as the nitrogen rich waste gases.

Ceramic membrane systems do not have storage capabilities unless the product gas is placed in pressurized gas storage cylinders. A second option, like the other technologies, would be the addition of a cryogenic cooler for storing the product gas in liquid dewars.

CRYOGENIC AIR SEPARATION

Cryogenic air separation for the purposes of this report means that refrigeration thermodynamic cycles and distillation, and possibly other processes are used to separate air into components so as to provide the aircraft with a source of oxygen or nitrogen enriched air either in the liquid or gaseous state. In most such applications, the air separation is enabled by the differences in boiling temperatures of oxygen and nitrogen. Use of cryogenic processes in aircraft systems has become more viable due primarily to three developments: miniaturized high speed turbomachinery using foil-bearing technology, miniaturized distillation columns for oxygen and nitrogen, and high efficiency thermal recovery devices. Three devices have been developed or are currently under development that are relevant to the purposes of this study. All are from Creare, Inc., Hanover, NH, and all have a specific purpose. These systems are the Advanced Hybrid Oxygen System for medical applications (AHOS-M), the Total Atmospheric Liquefaction of Oxygen and Nitrogen (TALON) system for potential use on the advanced C-17 cargo aircraft, and the Onboard System for Aircraft Fuel Tank lnerting (SAFTI) system for inerting fuel tanks of commercial aircraft.

AHOS-M is a modular, 2-man portable system that employs oxygen separation using PSA followed by liquefaction of the oxygen for storage in dewars for medical use as needed. The development of this system by the Air Force Research Laboratory at Brooks AFB was motivated primarily by the reality that military aircraft are being transitioned from a system using ground deployed LOX for aircraft servicing to an all OBOGS service. This change has impacted the availability of LOX stores for medical use. Development work on AHOS-M has been completed and a simplified schematic is shown in Figure 6.

The TALON system is presently targeted for use on the advanced C-17. TALON will not only eliminate current reliability and performance deficiencies of the current PSA-based OBIGGS installations but also meet oxygen supply needs aboard the aircraft for special operations, medical evacuation service, and other airplane uses where oxygen must be provided for military mission requirements involving many occupants in addition to the flight crew. TALON uses distillation columns, thermal recovery devices, and turbo-machinery configured in a reverse-Brayton cycle configuration to produce both LOX and liquefied NEA (LNEA). The TALON system is in the final design stage and is shown schematically in Figure 7.

SAFTI, the most recent cryogenic system proposed by Creare, is aimed exclusively at inerting the fuel tanks of commercial airplanes. SAFTI uses PSA technology to remove the oxygen from cabin air that has been compressed and re-cooled, as shown in the schematic of Figure 8.

The outflow NEA is then cooled first by a recuperator and then by heat exchange with neon working fluid cooled via reverse Brayton cycle. The NEA then goes to the distillation column and the product LNEA is sent to a cryogenic dewar for storage. Waste gas from the NEA distillation column is routed back through the inlet recuperator from whence it is further employed to purge the molsieves. NEA vapor from the top of the distillation column can be routed directly to the fuel tanks for inerting purposes. Creare's design approach for SAFTI is based on the fact that the inerting NEA volumetric rate requirements for commercial jets are much less severe than those associated with military tactical descents. Thus, using a modest LNEA storage capability, the SAFTI system can employ a small (hence, lightweight and low energy consumption) cryocooler unit operating throughout flight times of low NEA demand to build stored capacity to handle periods of high demand, i.e., taxi and takeoff. The basic differences between the militarized

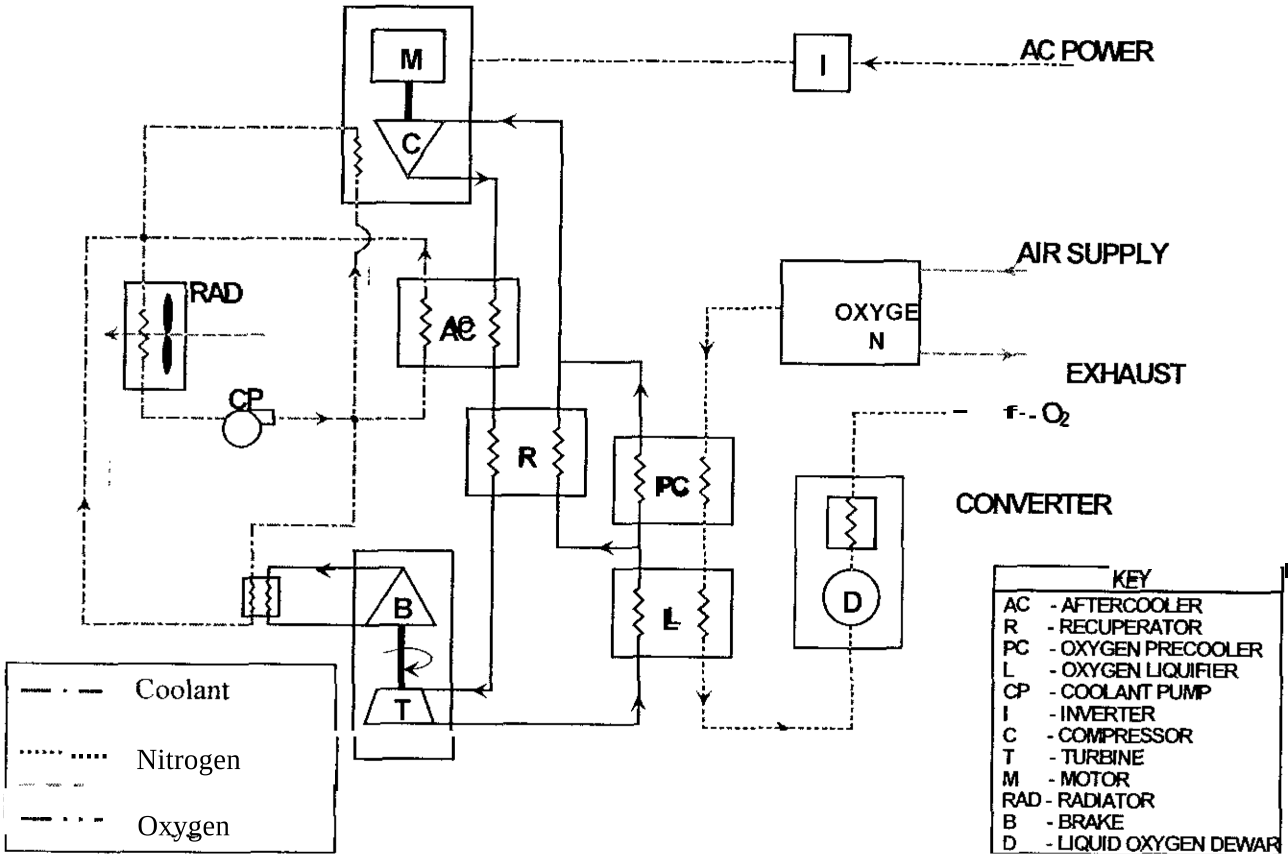


Figure 6. AHOS-M simplified schematic.

version of the TALON system that is capable of providing both LOX and LNEA and the commercial SAFETI system is that the latter is configured to provide only LNEA.

Hybrid Separation Devices

The various types of air separation devices can be combined in a variety of ways for purposes of increased product purity, utilization of the waste gas stream, and compensation for or capitalization on the available inlet air temperatures and pressures. Recirculation of gas through an air separation module (ASM) can also be of potential advantage. An example of a hybrid system would be a PSA unit in combination with a HFM device. In this case, the inlet stream would enter the HFM first and the primary product of the HFM will be NEA. If the HFM inlet pressure were higher than required for good unit efficiency, the pressure drop across the HFM device could be maintained at an optimum level by back pressure regulation of the HFM ASM. In this case, the secondary waste gas could exit the HFM at a high enough pressure to be useful in a PSA device. If the desired product from this stream were oxygen, then the PSA device could take advantage of the enhanced oxygen content of the HFM waste gas. If the inlet pressure to the HFM were only marginal for NEA production, then a compressor would be needed to boost the PSA inlet gas pressure to a level satisfactory for PSA operation. The need for such supplemental gas compression would make the hybrid concept less attractive.

Generally, hybrid systems equate to less flexibility in supply air parameters, less overall system reliability, higher weight, and higher installation and maintenance costs. In aeronautical applications, the hybrid systems will make most sense when there is a large imbalance between the normal nitrogen oxygen ratio in air and the ratio of product needed to service the aircraft needs.

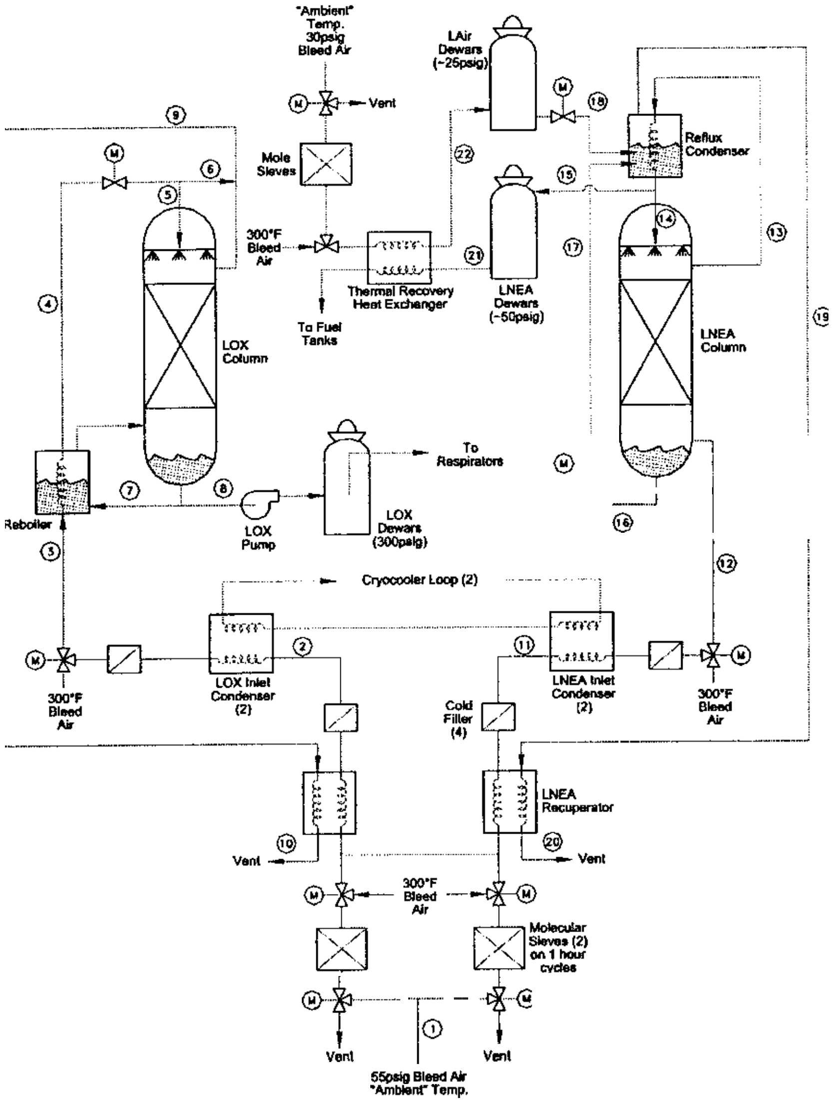
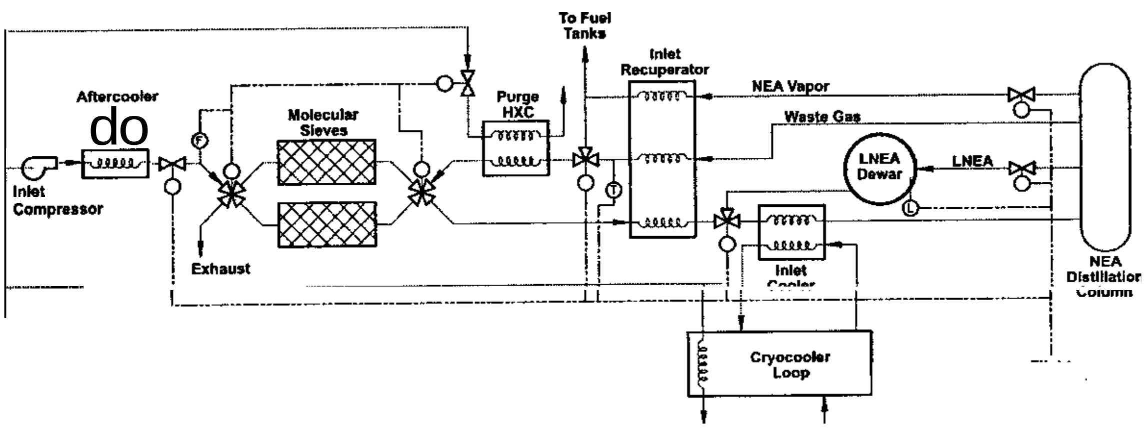


Figure 7. TALON functional schematic.



HYBRID APPLICATIONS

Hybrid applications are those where the air separation system is used in combination with another type device to achieve a desired result. An example is a cargo compartment fire suppression system that employs a water mist or pyrotechnic aerosol to initially knock down the **fire** and then continued metering of NEA from an OBIGGS installation to suppress the fire for the remainder of the flight. A hybrid application alluded to earlier was a trickle charge device for the high pressure oxygen bottles used in some aircraft models [4]. This system used a small PSA unit followed by a compressor to provide the 99% pure oxygen to top off the airplane stored oxygen. The benefits of this system were to reduce the amount of ground servicing required for the oxygen system with the many attendant costs and risks associated with such maintenance and support.

Availability of cryogenic liquids on **an** aircraft may enable development or deployment of technologies on commercial jet aircraft that have not been possible up to now. Availability of sufficient LOX at appropriate times could permit deployment of super efficient, lightweight APUs. The absence of nitrogen in the oxidizer supply eliminates the problem of nitrogen oxide emissions. Availability of LNEA can provide a cooling capability as well **as** low temperature environments that would enable high efficiency alternators and motors along with other superconductor benefits.

NANOPORE TECHNOLOGY

The journal ***Science*** reported on development work being conducted by the Department of Energy Sandia National Laboratories, using ultraviolet beams of light to provide precise size adjustments in the pores (nanopores) of membranes and the crystalline structures of Zeolites [5]. The multi-institutional development work is being performed under the leadership of Dr. Jeffery Brinker. (His team's work has been published as a four-paper series in the journal ***Nature***, which details their inquiries into the properties of nanostructures that self-assemble to produce repeating patterns of pores of exactly the same size.) The honeycomb-like structures have pores that shrink in unison when illuminated by the ultraviolet beam of light. The ability to "tune" membrane and crystalline structures will enhance the capabilities of the membranes to optimize separation of oxygen and nitrogen. Initial application of this new nano-technology is for sensor arrays, nanoreactors, photonic and fluidic devices, and low dielectric-constant films.

CONCLUSIONS

It is the opinion of the author, based on the current state of the art for the technologies investigated, that none of the technologies except the Creare TALON and SAFTI cryogenic systems appears able to meet the requirements for *full-time* fuel tank inerting of all fuel tanks, unless it has the cryogenic storage capabilities required to meet peak demand conditions.

Assuming that the fuel tanks will be required to be inert to <9% oxygen concentration before push back from the boarding gates will be allowed, existing on board systems will not have the bleed air or electrical power available that is required to operate the different systems available. The engines will not be operating at the boarding gates. To meet a "push back" inerting requirement alternate power and compressed air sources must be provided, or a nitrogen gas ground cart to "top off' the fuel tanks before pushback.

This latter point gives rise to the need and probable requirement that the aircraft will need to be equipped with on-board systems, otherwise its operation is limited to those gates and airports with ground service capabilities. Any failure of a centralized ground cryogenic plant could have significant economic impact for all carriers operating from this particular airport as all airplanes would be grounded for revenue flights. To mitigate the high cost of implementing centralized cryogenic plants and/or ground service carts, and the potential for complete loss of an airport from mechanical failure, weather or natural disaster, or from terrorists acts, on-board systems seemingly offer the least overall system impact.

Before any system can be fully engineered for any airplane, an exact set of certification or performance standards must be specified. For example, requiring heated center fuel tanks to have an oxygen concentration of 9% or less prior to push back from the boarding gate, or requiring full time inerting to 10% oxygen concentration during all phases of flight are hard performance based design requirements. Flammability issues may also be considered in combination with performance based requirements which would allow different design approaches, again to qualify against performance based specifications.

From a technology maturity point, only the molecular sieves and hollow fiber membranes are off the shelf today. These are capable of producing **O,** and N, gases in the desired purity ranges. Whether these technologies can produce the purity of gases at the volumes and pressures required without supplemental systems, i.e., compressors or cryogenic storage, again depends on design and performance requirements and operational limits of the aircraft.

New technologies such as ceramic membranes and gas liquefaction systems can produce virtually pure gases. In the case of ceramic membranes, 100% pure oxygen is produced by ion transport across the membranes at high temperatures. Cryogenic production and storage of gases as liquids offers additional flexibility through its inherent liquid storage capability. By introducing cryogenic cooling into a gas production system, the desired gas can be stored for subsequent use, **i.e.,** LNEA for inerting at pushhack. In the matter of oxygen required for emergency depressurization and descent, a large volume of gas is required very quickly, which would preclude considering any system that would have “startup” lags to get up to desired performance. Cryogenic storage would eliminate startup lag by having a ready supply of gas stored as a liquid. The USAF Research Laboratory development of the AHOS-M medical oxygen system is a good example of combining gas separation and cryogenic cooling and storage of oxygen. Cryogenic liquids require much smaller volumetric space at significantly lower pressure for storage than high pressure compressed gases and have a much lower impact on maintenance and eliminate high pressure gas bottles logistics, inventory and pressure testing.

As aircraft increase in size and/or passenger capacity, route flexibility and aircraft utilization will become more important to these high value assets. Any technology that increases their operating performance or route flexibility should be given serious consideration as they will increase asset utilization and operations flexibility. A 600-800 passenger aircraft would require a very heavy emergency oxygen system, and, if flying a trans-Himalayan, an even heavier compressed oxygen system would be necessary to maintain required altitude during an emergency depressurization over extended periods. A cryogenic oxygen or LOX system would be significantly smaller and lighter in weight and have a lower fuel bum than a comparable compressed gas system. One liter of LOX at 200 psi will expand to approximately 860 liters of oxygen gas whereas a 2000 psi compressed gas system will expand at 201:1.

Gas separation technology systems that can operate with a higher duty cycle can’be sized smaller at a reduced output if the product gases are stored as liquids. Since there is not a continuous demand, rather peak demands such as at push back or in an unlikely emergency descent, the gases can be generated at a much lower rate and stored to make up for usage. This eliminates the requirement for large quantities of electrical power and high pressure engine bleed to produce the product gases when the airplane is least able to provide it, **i.e.,** while at the gate and taxi for takeoff.

Whereas LOX systems have been in common use in various military aircraft, they have not seen use in commercial aircraft outside of Air Force One. Use in commercial aviation will be a major departure from the more established and tradition design philosophy, more so than changing from compressed gas cylinders to chemically generated oxygen. But one nonetheless, cryogenic gas storage needs to be considered for future aircraft applications.

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